Mapping the Asymmetric Thick Disk: The Hercules Thick Disk Cloud

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ABSTRACT

The stellar asymmetry of faint thick disk/inner halo stars in the first quadrant (l = 20 –45°) first reported by Larsen & Humphreys (1996) and investigated further by Parker et al. (2003, 2004) has recently been confirmed by the SDSS (Jurić et al. 2008). Their interpretation of the excess in the star counts as a ringlike structure, however, is not supported by critical complementary data in the fourth quadrant, not covered by the SDSS. We present stellar density maps from the Minnesota Automated Plate Scanner (MAPS) Catalog of the POSS I showing that the overdensity does not extend into the fourth quadrant. The overdensity is most probably not a ring. It could be due to interaction with the disk bar, evidence for a triaxial thick disk, or a merger remnant/stream. We call this feature the Hercules Thick Disk Cloud.

Subject headings: Galaxy: structure, Galaxy: kinematics and dynamics

1. Introduction

Larsen & Humphreys (1996) initially reported a substantial asymmetry of faint blue stars in the first quadrant (Q1) of the inner Galaxy, $l = 20° - 45°$ compared with complementary fields in the fourth quadrant (Q4) based on star counts from MAPS[1] (Cabanela et al. 2003). Parker et al. (2003) made a more in-depth survey to map the extent of the asymmetry using 40 contiguous fields in each of three regions: Q1 above and below the plane and Q4 above the plane. Q4 below the plane is not covered in the POSS I. They found a 25% excess in the number of probable thick disk stars in Q1 above *and* below the plane when compared to the complementary Q4 fields. The region was irregular in shape and covered several hundred square degrees, but with a completeness limit at $\approx$ 18–18.5 mag, the stars showing the excess in Q1 were relatively nearby, $\sim 1 - 2$ kpc from the Sun. Parker et al. (2004) also found an associated kinematic signature, a significant lag of 80 to 90 km/sec in the direction of Galactic rotation for the associated thick disk stars in Q1.

The recent release of the SDSS Data Release 5 (DR5) photometry in the direction of the observed asymmetry in Q1 led to the discovery of a feature at much fainter magnitudes, the distant Hercules-Aquila cloud (Belokurov et al. 2007) and the photometric parallax study by Jurić et al. (2008) confirmed our nearer asymmetry in the inner Galaxy as an overdensity at a galactocentric radius of 6.5 kpc situated 1.5 kpc above the plane. The SDSS survey however is not well designed for a good study of the thick disk inside the Solar orbit. It extends below $b = 30°$ in only a few directions in Q1 and has only limited coverage in Q4.

We are continuing our program of photometric and spectroscopic observations to map the size and extent of the asymmetry along our line of sight and to determine the degree of spatial and kinematic asymmetry above and below the plane. We are using the SMARTS Consortium CTIO 1-meter Y4KCam and the Steward Observatory 90" Bok telescope 90Prime Mosaic imager to obtain wide-field multi-color CCD imaging to fainter completeness limits than the POSS I. Spectra of the candidate thick disk stars for radial velocities and metallicity estimates have been observed using the Hydra multi-object spectrometer on the CTIO Blanco 4-meter telescopes and the Hectospec on the MMTO 6.5 meter.

In this Letter we present a stellar number density map we created from the MAPS POSS I scans to provide a more global reference for our current deeper but more spatially restricted photometric and spectroscopic study of the thick disk in the inner Galaxy. Other works (Xu et al. 2007) have used plate data to supplement gaps in the SDSS at more southern declinations with good success. Our map of the stellar density in Q1 and Q4 covers much of

[1]The Minnesota Automated Plate Scanner Catalog of the POSS I is online at: http://aps.umn.edu

the sky unavailable to SDSS and demonstrates that the nearby asymmetry in Q1 does not represent a ring above the Galactic plane, but instead is a significant substructure or cloud extending over many square degrees in galactic longitude and latitude. We call this feature the Hercules Thick Disk cloud.

2. The Stellar Density Maps

The figures presented in this Letter were originally created to provide a reference frame for the interpretation of our ongoing observations of the thick disk using narrower yet deep multicolor CCD imaging. They were made using the same set of POSS I fields selected by Parker et al. (2003) above the galactic plane and the fields are fully described in that publication. The 80 POSS I plates cover 2900 square degrees on the sky and all are complete to fainter than 18th magnitude in the O band (blue) and have colors (O–E) available from the paired observation in the red (E band). Their placement on the sky is shown in Figure 1 for Q1 and for Figure 2 for Q4. The B-V extinction in each field is plotted from Schlegel et al. (1998) and is substantially less than $E(B-V) < 0.2$ in all fields. We defer a discussion of the Q1 data below the plane to a later paper because it is not relevant to the present Letter. The MAPS Catalog has superior stellar photometry when compared with most other digitized plate catalogs of the POSS because each plate has its own independent photometric calibration derived from our own CCD observations as described in Larsen & Humphreys (2003) or from photoelectric photometry (Lasker et al. 1988) and uses an isophotal diameter-to-magnitude relation for the stars.

The individual plate catalogs were merged, duplicates in the plate overlap regions removed, and interstellar extinction from Schlegel et al. (1998) was applied on a star by star basis using the standard interstellar extinction law. We assume that the bulk of the extinction comes from relatively near the Sun and that our objects of interest are much farther away, so that the extinction is a zero point correction. A global geometric vignetting correction was applied to all of the plates in the MAPS Catalog. However, we found that some plates had larger vignetting problems (probably due to moonlight). As a result we applied an additional radial magnitude correction to the MAPS magnitudes for 5 of the 80 plates to bring the number densities at the plate edges into line with the well behaved and well calibrated plate center. Star-galaxy classification uses a neural network (Odewahn et al. 1992, 1993) and is described in those papers and in Cabanela et al. (2003). Any uncertainty in object classification is not a significant factor in the creation of these maps.

We then selected stars in the magnitude range $14 < O < 18$ (or approximately $13.5 < V < 17.5$) above the completeness limits. Since the plates still have some magnitude zero

point differences and cosmic scatter, we used the "blue ridgeline" at $O-E \approx 1.0$ or $B-V \approx 0.6$ as a fiducial reference to select a sample of stars with blue and intermediate colors (see Parker et al. 2003, Fig.5). Stars bluer than the ridgeline are representative of the stars which show the asymmetry (Parker et al. 2003). While the exact location of the blue ridge in O-E color varies somewhat from plate to plate and with galactic longitude and latitude, due to the relative contributions of stars from the halo, disk and thick disk, it provides a strongly identifiable feature on each color-magnitude diagram (see Figure 3). The color variations between adjacent plates will thus be small compared to the variations across the full 180 degrees of sky covered. Our magnitude and color search limits are illustrated on one of our color magnitude diagrams shown in Figure 3.

3. Discussion and Conclusions

After the reduction steps outlined above, we then binned the stars $0.25° \times 0.25°$ in l and b to create maps of the stellar density distribution of the faint blue and intermediate color stars shown in Figures 4 and 5. The figures are color-coded with respect to number density per 0.0625 square degree.

Jurić et al. (2008) described the excess in Q1 as due to a "ringlike" structure because the overdensity appeared to be radially constant and circular in cross section in their Figure 27. The center of the overdensity region ranges from $(X, Y, Z) = (6.5kpc, -2.2kpc, 1.5kpc)$ to $(6.5kpc, 0.3kpc, 1.5kpc)$ and can easily be converted into galactic coordinates. This is shown as the purple line on Figure 4. If the feature were symmetric about $l = 0°$ it would project into Q4 to $(6.5kpc, 2.2kpc, 1.5kpc)$. This projection is also shown as a purple line on Figure 5. Comparison of Figures 4 and 5, however show that the density of these stars is not symmetric with respect to the Sun-Center line. There is a clear excess of stars in Q1 over Q4 in the range $l = 25 - 45°$ and $b = 30 - 40°$. Furthermore, we emphasize that the excess would not have been initially discovered if it had been a symmetric ring since we (Larsen & Humphreys 1996) were comparing star counts for complementary fields in Q1 and Q4.

Could the "ringlike" structure be inclined to the plane and therefore not visible in Q4? Most probably not. The full height of the overdensity in Z over an azimuthal distance of 2500 parsecs is only 500 pc (Juric̀¸ et al.). Even for the pathological case of a paper thin inclined distribution in Z the maximum inclination could only be 11 degrees and given its width in X it should have been visible in Figure 5. Additionally, there is strong evidence from Jurić et al.'s Figure 27 (left panel) that for X = 7250-7750 parsecs the overdensity is exclusively above Z = 1500 pc. Examination of the same figure's middle panel shows

that all significant contributors to the overdensity in this same X range have $Y < 1000$ pc. This would be the opposite of what should be happening if the overdensity were falling into the plane in Q4. Finally, Parker et al. (2004) studied the velocities of samples of stars taken from overdensity regions in Q1 compared with a control sample Q4 and found in a somewhat weak result that the Z component of velocity was less negative for Q1 than it was for Q4. If a coherent population of stars were moving together towards the disk from above the plane as they entered Q4, the opposite should be true.

The cloud of stars detected by Jurić et al. is not symmetric about the $l = 0°$ line and almost certainly is not a ring. This does not change their other possible explanation for the feature, however. Given the broad extent of the cloud (Figures 4 and 5) together with its apparent small ranges in radial distance from the Sun and its distance above the galactic plane (their Figure 27), the Hercules Thick Disk cloud may be a debris stream consistent with the disk formation scenario described by Abadi et al. (2003). While the Hercules Thick Disk Cloud is relatively nearby on the sky it is not related to the more distant (10 - 20 kpc) Hercules-Aquila cloud of (Belokurov et al. 2007). The northern extent of the Hercules-Aquila cloud (Figure 2 in Belokurov et al. (2007)) is confined to galactic latitudes less than 30° and even in those regions the bulk of the stars are much fainter than our magnitude limit. The contamination of our sample by Hercules-Aquila cloud stars would be less than 5 objects per square degree (0.5 stars/bin) in any case given our relatively bright magnitude limits.

Other explanations are still possible such as a triaxial thick disk and an overdensity due to an interaction with the disk bar. Analysis of our CCD photometry and spectroscopy for fainter stars in Q1 and Q4 will be used to address this question.

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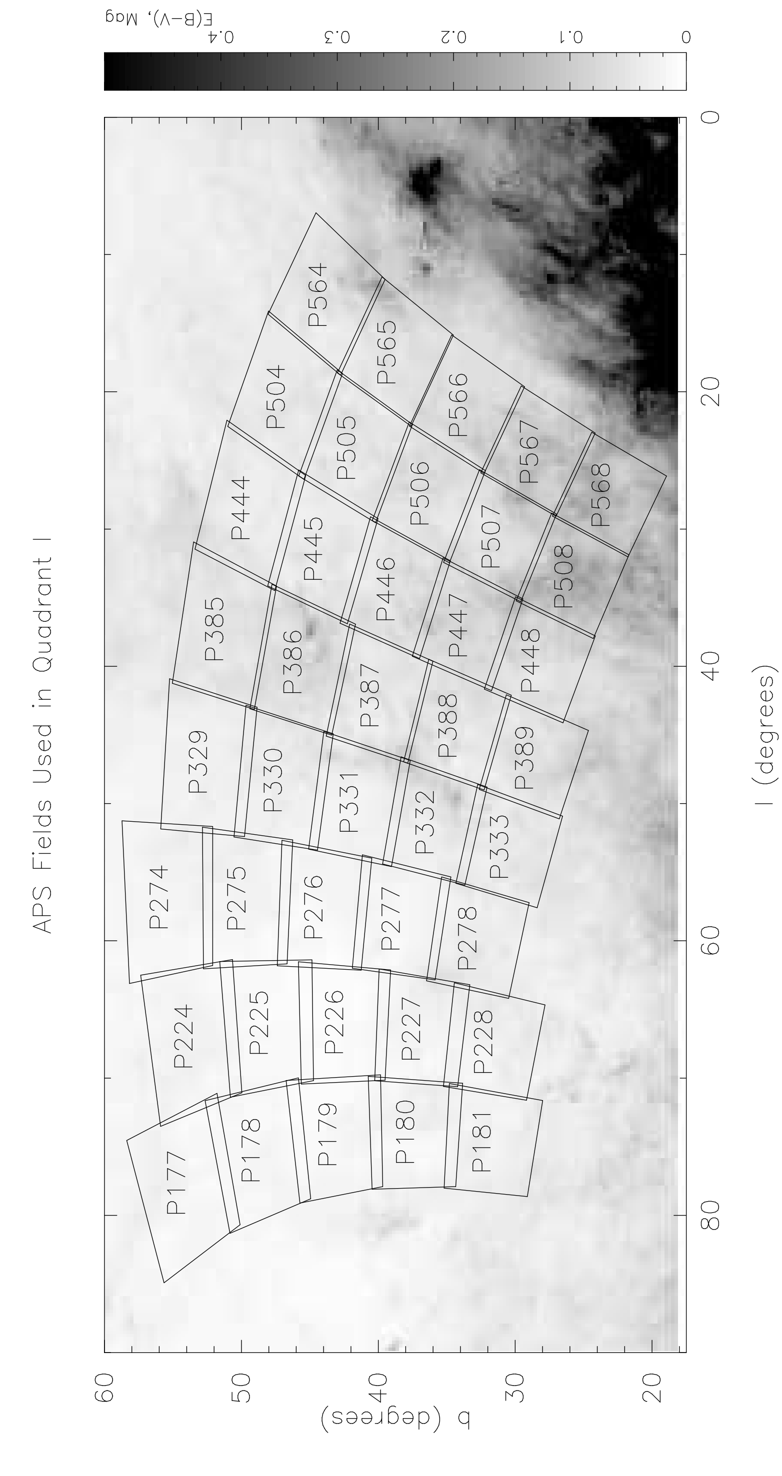

Fig. 1.— The fields from the MAPS Catalog of POSS I used to create the star count areal density image for Q1 ($l = 0° - 90°$). The centers are further described in Parker et al. (2003) and are superimposed on the extinction plots of Schlegel et al. (1998). While the interstellar extinction is clumpy it is not high enough to influence our primary result.

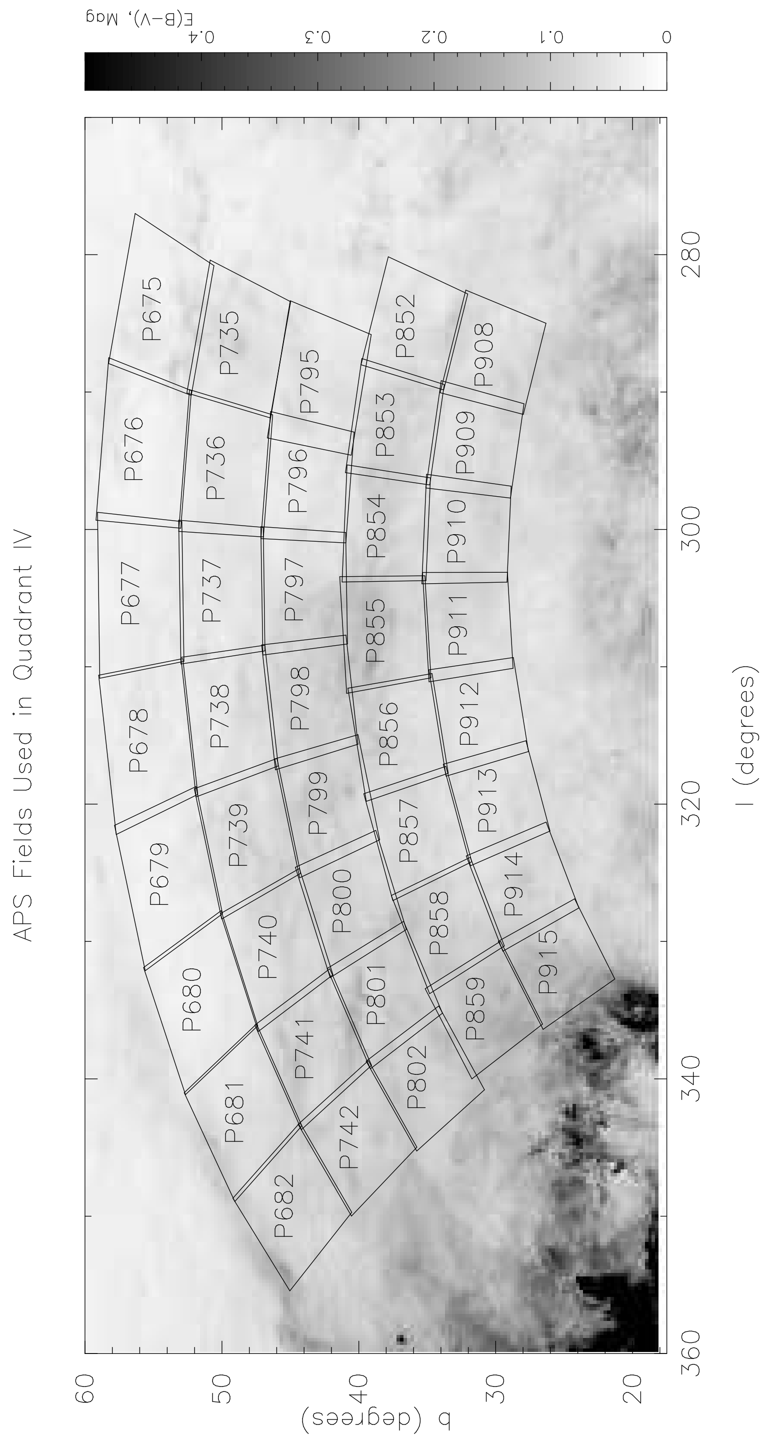

Fig. 2.— The fields from the MAPS Catalog of POSS I used to create the star count areal density image for Q4 ($l = 270° - 360°$). The centers are further described in Parker et al. (2003) and are superimposed on the extinction plots of Schlegel et al. (1998). While the interstellar extinction is clumpy it is not high enough to influence our primary result.

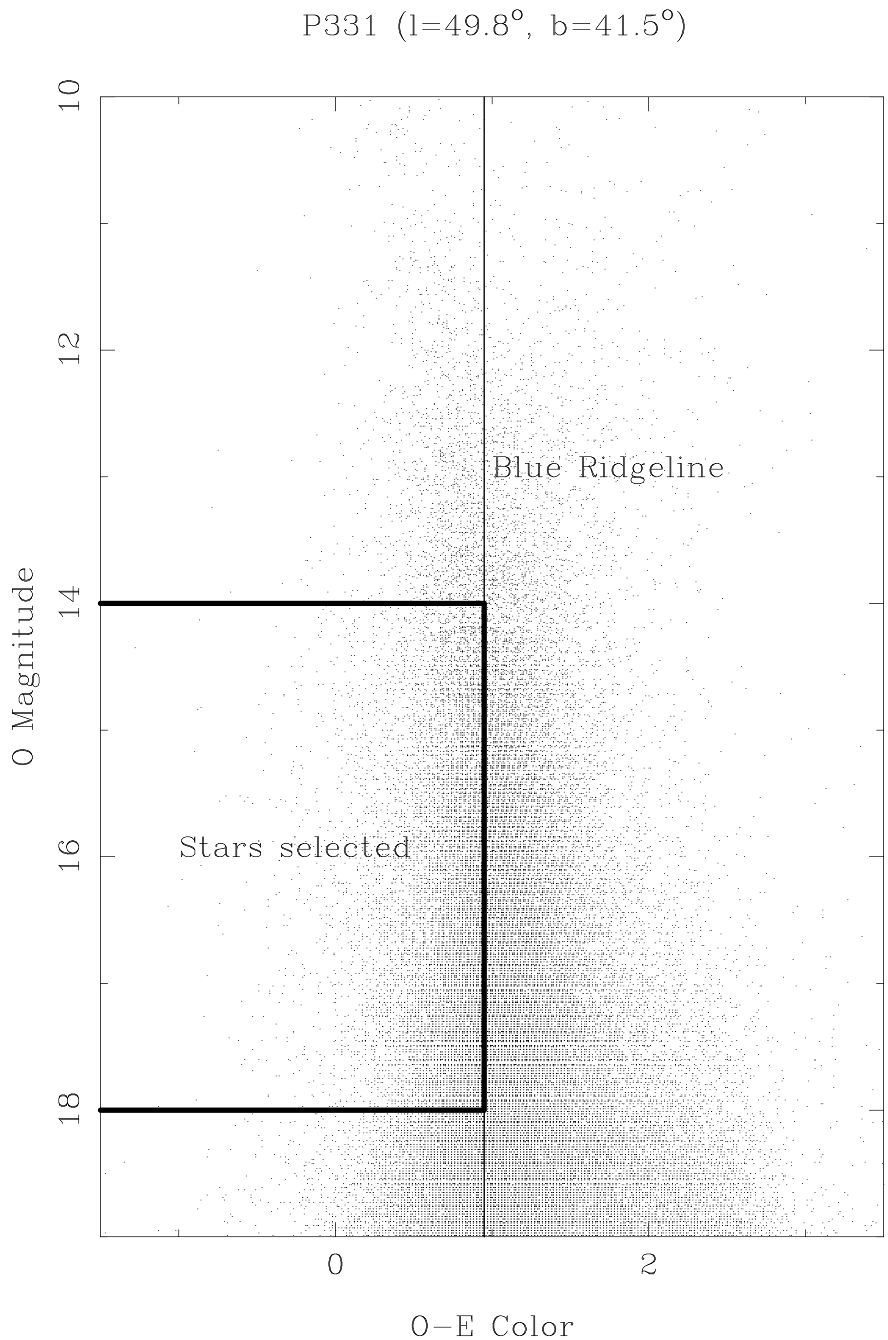

Fig. 3.— An example Color Magnitude diagram from the MAPS Catalog indicating the region of color and magnitude used to generate these images.

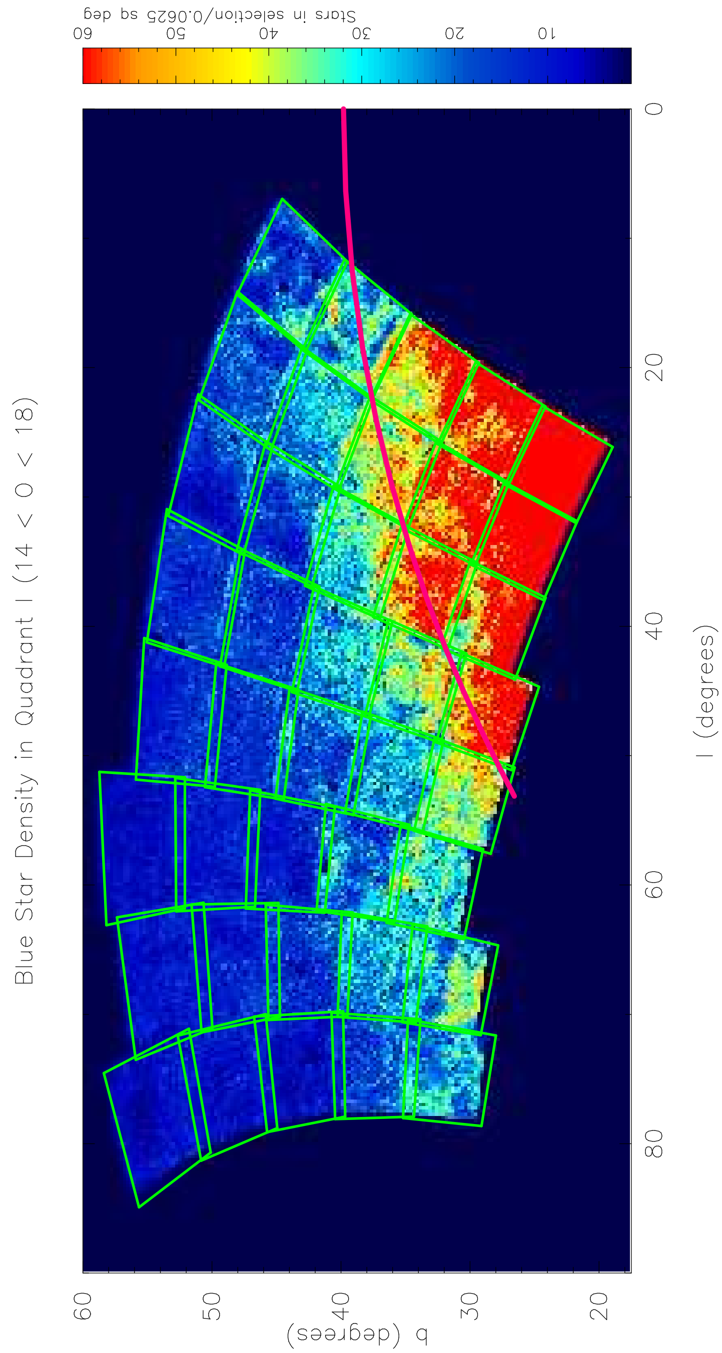

Fig. 4.— The density image created for the stars in Q1 with the POSS I plate boundaries from Figure 1 overlayed in green. Notice how there is a distinct overdensity on the order of about 30% between $l = 25° - 45°$ and $b = 30° - 35°$ when compared with the corresponding Q4 stars in Figure 5. Comparison with Figure 1 shows that extinction cannot be causing the feature we see. The location of Juri¸ et al.'s overdensity is shown by the purple line.

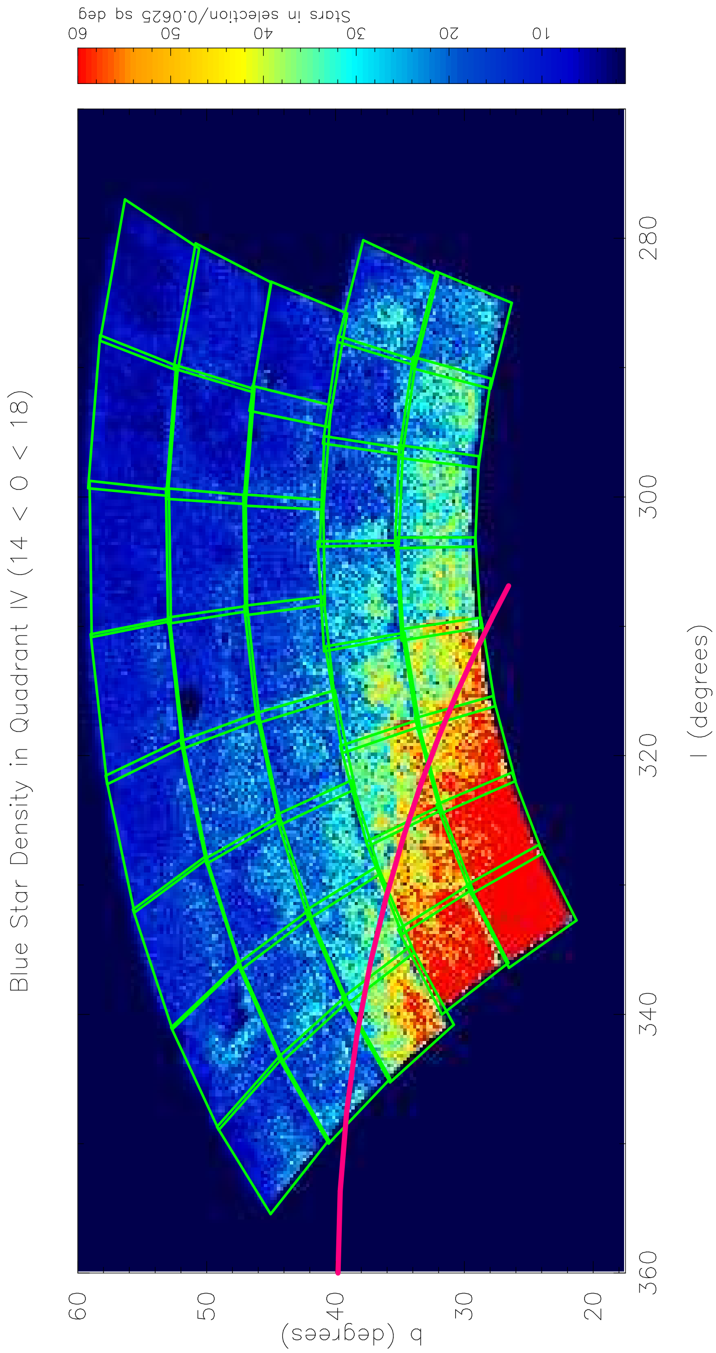

Fig. 5.— The density image created for the stars in Q4 with the POSS I plate boundaries from Figure 1 overlayed in green. There is no enhancement of faint blue star counts between $l = 335° - 315°$ to match the excess shown in Figure 4. Comparison with Figure 2 shows that extinction cannot be hiding this lack of stars. The location of the Q4 projection of Juri¸' et al.'s overdensity is indicated by the purple line.